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Rong-Hua Guan[a]; Yu-Bao Sun[b]; Guang-Sheng Fu[b]
[a] Department of Applied Physics, North China Electric Power University, Baoding, People's Republic of China [b] Department of Applied Physics, Hebei University of Technology, Tianjin, People's Republic of China

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Rong-Hua Guan[a], Yu-Bao Sun[b]* and Guang-Sheng Fu[b]

[a]*Department of Applied Physics, North China Electric Power University, Baoding 071003, People's Republic of China;* [b]*Department of Applied Physics, Hebei University of Technology, Tianjin 300130, People's Republic of China*

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The response times of Pi-cell liquid crystal displays with an arbitrary pretilt angle were calculated under different drive methods. Using the normal drive method, the results show that the rise and off times of the cell driven by high voltage are faster than those driven by low voltage. However, the off time is very fast for the cell with non-zero critical voltage driven by low voltage when we use the under-shoot method.

Keywords: liquid crystal display; Pi-cell; response time; under-shoot method

1. Introduction

Many applications of liquid crystal displays (LCDs) require fast response speeds. For example, colour sequential LCDs require the LC response speed to be fast. A ferroelectric LC has very fast response speed but it lacks grey and requires difficult processing (1). The Pi-cell (2) [also known as the optically compensational bend (OCB) (3) cell] exhibits a fast response characteristic. The Pi-cell operates between the bend deformation at a critical voltage (U_c) and the near homeotropic state at high voltage. Many researchers (*4–10*) have only studied the response times of the cell with various pretilt angles when it is switched between U_c and the on-state voltage. However, the response time is sensitive to different drive voltages and pretilt angles, but this has not been analysed in detail previously.

In this letter, we calculate the response time of the Pi-cell with arbitrary pretilt angle driven by different voltages, and using normal and under-shoot method in the off process. Our results show that the response times strongly depend on the voltage and the pretilt angle. The response times (both rise and off times) of the cell driven by large voltage are faster than that of the cell driven by low voltage using the normal drive method. However, for the off time, the response is much faster for the cell driven by low voltage than that of the cell driven by high voltage using the under-shoot method. In the following numerical calculation, the LC E7 material parameters are chosen as n_e=1.65, n_o=1.5, $\Delta\varepsilon$=13.745 (=19.24−5.495), K_{11}=10.6 pN, K_{33}=15.5 pN, γ=0.15 Pa s, η_1=0.1732 Pa s, η_2=0.0232 Pa s and η_{12}=0.0 Pa s (7, 8). The same cell gap (3 μm) is used in our simulation to compare with the various pretilt angle and voltage effects on the response times.

2. Theory and simulation

For a brief discussion, the relationship between the electric field in the LC layer and the drive voltage can be written as $E \approx U/d$. Taking into account the flow effect, the dynamic equation for the cell switching in the bend state can be described by (*7–10*)

$$\gamma * \frac{d\theta}{dt} = \left(K_{11}\cos^2\theta + K_{33}\sin^2\theta\right)\frac{\partial^2\theta}{\partial z^2} + \left[\left(K_{33}-K_{11}\right)\left(\frac{d\theta}{dz}\right)^2 + \varepsilon_0\Delta\varepsilon E^2\right]\sin\theta\cos\theta, \quad (1)$$

where the relation between the effective rotational viscosity (γ*), the rotational viscosity (γ) and Miesowicz viscosity constants (η_i) is determined by

$$\gamma * = \gamma\left(1 - \frac{\left[\frac{1}{2}\left(1-\frac{\eta_1-\eta_2}{\gamma}\right)\cos^2\theta + \frac{1}{2}\left(1+\frac{\eta_1-\eta_2}{\gamma}\right)\sin^2\theta\right]^2}{\frac{\eta_{12}}{\gamma}\sin^2\theta\cos^2\theta + \frac{\eta_1-\eta_2}{\gamma}\sin^2\theta + \frac{\eta_2}{\gamma}}\right) = \gamma F(\theta), \quad (2)$$

where $F(\theta)$ is less 1.0, which means that γ* is always less than γ (7). We analyse the response time by using Equation (1) and the small-angle approximation. The LC tilt angle change with time and z, and LC profile for the decay and rise processes can be written as follows (*11*):

$$\theta_{off}(z,t) = \theta_0(z) + \theta_c\sin\frac{2\pi z}{d} + \theta_m\sin\frac{2\pi z}{d}\exp\left(-t/\tau_{off}\right), \quad (3a)$$

$$\theta_{on}(z,t) = \theta_0(z) + \theta_c\sin\frac{2\pi z}{d} + \theta_m\sin\frac{2\pi z}{d}\left[1-\exp(-t/\tau_{rise})\right], \quad (3b)$$

where θ_c is the maximum change of LC from $\theta_0(z)=\theta_p+(\pi-2\theta_p)z/d$ as the cell is driven by U_c, θ_p is the pretilt angle, θ_m is the maximum deformation of LC

*Corresponding author. Email: hmtj450@vip.sina.com

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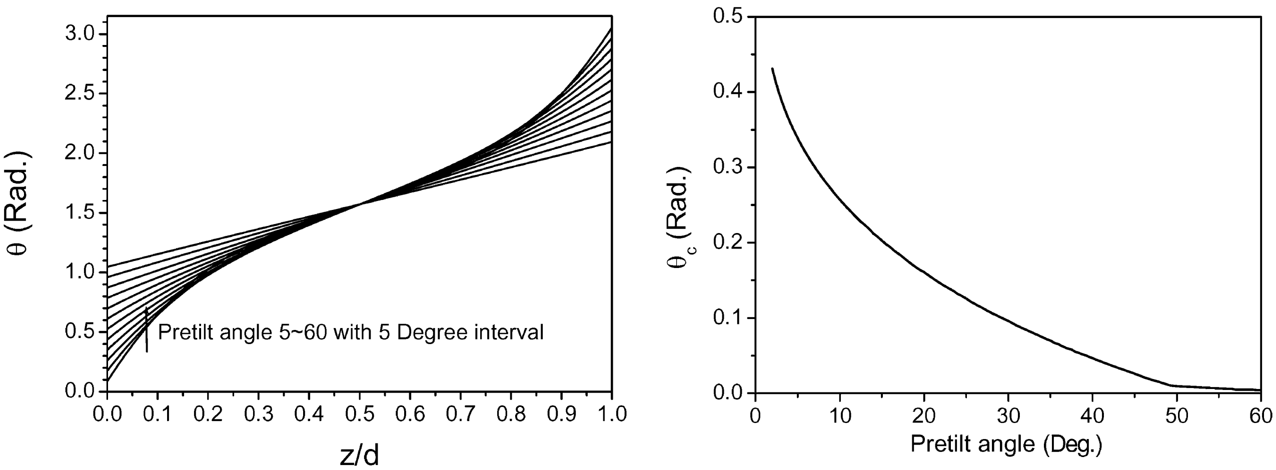

(a) (b)

Figure 1. The LC profile (a) and θ_c (b) under the critical voltage for different pretilt angles.

under the driven field from the profile of LC under the critical field (*12*). The LC profile under U_c can be calculated using Equation (1), as shown in Figure 1a, and θ_c is shown in Figure 1b for the various pretilt angles.

In the processes of obtaining the rise and off time, we use one elastic parameter approximation ($K_{11}=K_{33}=K$) and let $t=\tau$ (*9, 11, 13*). Substituting Equation (3a) into Equation (1), the off time for the cell switched from on-state to U_c is obtained as

$$\tau_{off}=\frac{\gamma d^2}{4\pi^2 K}\int_0^{d/2}\frac{\theta_m}{\exp(1)}F(\theta)\sin\frac{2\pi z}{d}dz\Bigg/\int_0^{d/2}\left[\begin{matrix}(\theta_c+\theta_m\exp(-1))\sin\frac{2\pi z}{d}\\-(E_c/E_0)^2\sin\theta\cos\theta\end{matrix}\right]dz, \tag{4}$$

where $\theta=\theta_0(z)+(\theta_c+\theta_m\exp(-1))\sin\frac{2\pi z}{d}$ and $E_0=\frac{2\pi}{d}\sqrt{\frac{K}{\varepsilon\Delta\varepsilon}}$, which is twice that of the threshold electric field of a Freedericksz cell, and E_c is the critical electric field, which is equal to the ratio of the critical voltage and the cell gap ($E_c\approx U_c/d$). Under a drive voltage, the rise time can be calculated by substituting Equation (3b) into Equation (1):

$$\tau_{rise}=\frac{\gamma d^2}{4\pi^2 K}\int_0^{d/2}\frac{\theta_m}{\exp(1)}F(\theta)\sin\frac{2\pi z}{d}dz\Bigg/\int_0^{d/2}\left(\begin{matrix}(E/E_0)^2\sin\theta\cos\theta-\\ [\theta_c+\theta_m(1-\exp(-1))]\\ \sin\frac{2\pi z}{d}\end{matrix}\right)dz, \tag{5}$$

where $\theta=\theta_0(z)+[\theta_c+\theta_m(1-\exp(-1))]\sin\frac{2\pi z}{d}$, and E is the on-state electric field.

To achieve a faster rise time, the cell is driven by a high voltage. As the LC profile arrives at the appropriate state of a grey-level, the voltage for this grey-level is added to hold the state; this method is also called the over-drive method. The rise time can be further reduced using this drive method. To improve the decay time, the off-state voltage should be reduced to zero, and U_c is added to hold the material in the bend configuration as the LC material relaxes to its proper state during the decay process. This method is called the under-shoot method. Because the LC changes from the on-state to the state under U_c, not from the on-state to the state under $U=0$, the change of tilt angle is $\theta_m\sin(2\pi z/d)$, the decay time τ_d(u) is also defined as the interval time of the tilt angle change from $\theta_0(z)+(\theta_c+\theta_m)\sin(2\pi z/d)$ to $\theta_0(z)+(\theta_c+\theta_m\exp(-1.0))\times\sin(2\pi z/d)$. Equation (3b) can not be used for the under-shoot method because of the free relaxation in the decay process. Considering the decay process of the cell driven by the under-shoot method, the LC configuration firstly undergoes free relaxation of the following form because of the drive voltage is zero:

$$\theta_{decay}(z,t)=\theta_0(z)+(\theta_c+\theta_m)\sin\frac{2\pi z}{d}\exp(-t/\tau_{decay}), \tag{6}$$

where τ_{decay} is the decay time for the cell to change from the state under U_{on} to the off-state under $U=0$. This is easily obtained as $\tau_{decay}=\gamma^* d^2/(4\pi^2 K)$ by substituting Equation (6) and $U=0$ into Equation (1). When the LC configuration reaches the state under U_c, the critical voltage, U_c, is applied to stop the motion of the LCs. Considering the definition of the decay time and free relaxation process of the LCs, we obtained

$$\tau_d(\mathrm{u})=-\tau_{decay}\ln\left(1-\frac{\theta_m[1-\exp(-1.0)]}{\theta_c+\theta_m}\right). \tag{7}$$

When θ_m is much smaller than θ_c, Equation (7) can be reduced to

$$\tau_d(\mathrm{u})=\frac{\tau_0}{4}\frac{\theta_m[1-\exp(-1.0)]}{\theta_c+\theta_m}F(\theta), \tag{8}$$

where $\tau_0=\gamma d^2/(\pi^2 K)$ is the decay time of a Freedericksz cell and $F(\theta)$ varies with z. As an approximation, we can use a mean value, $\overline{F(\theta)}=\frac{2}{d}\int_0^{d/2}F(\theta)dz$, instead of $F(\theta)$and then we can analyse the decay time using this equation. In the above equation, the factor 4 in the right term means the half-cell effect, and it is also suitable for Equations (4) and (5). For the cell with non-zero critical voltage, θ_c decreases as the pretilt increases (*12*), so the decay time of the cell with low pretilt is less than that of the cell with high pretilt from Equation (8). For the cell with zero critical voltage, θ_c is zero or too small compared with θ_m, and Equation (7) can be rewritten as

$$\tau_d=\frac{\tau_0}{4}\overline{F(\theta)}. \tag{9}$$

The decay time is linearly proportional to $\overline{F(\theta)}$ and decreases with increasing pretilt angle. For a given pretilt, it also decreases with the increasing on-voltage because of the distribution of tilt angle.

The response time is evaluated as a function of the maximum deformation (θ_m) of LC, as shown in Equation (3). U_c for a cell with an arbitrary pretilt can be calculated using the results of previous work (*12*, *14*). Using the LC parameters, the critical pretilt angle is 47.7° and the bend state is the stable state since the pretilt is larger than the critical pretilt. That is, the cell has zero critical voltage if the pretilt is larger than 47.7°. Used Equation (1), θ_c (for various pretilt angles) and θ_m are obtained, and the response times are obtained simultaneously. Substituting θ_c, θ_m and V_{on} into Equation (5), the rise time can be calculated; substituting θ_c, θ_m and U_c into Equation (4), the off time can be calculated. θ_c for various pretilt angles and θ_m for different drive voltages can also be obtained from the equilibrium equation.

We set the on-state voltage (V_{on}) from U_c to U_c+5 V with 0.5 V intervals and the voltage changes from U_c to V_{on} (on case) and from V_{on} to U_c (off case). In order to use Equations (4) and (5), a mean geometric elastic constant ($K=\sqrt{K_{11}K_{33}}$) (*9*) is used as the elastic parameter. The rise times, calculated using Equation (5) and numerically simulated by Equarion (1), are shown in Figures 2(a) and 2(b), respectively, for the Pi-cell with different pretilt angles. As can be seen in Figure 2, the results obtained using Equations (5) and (1) are very similar to each other. The rise time decreases as the drive voltage increases, but has no more change for low drive voltage and decreases rapidly as the pretilt angle increases, which is also confirmed partially by previous experiment data (*5, 10*). To achieve a faster rise time, the cell is driven by a high voltage. As the LC profile arrives at the appropriate state of a grey-level, the voltage for this grey-level is added to hold the state; this method is also known as the over-drive method.

The off times, calculated using Equations (4) and (1) for the cell switched from V_{on} to U_c, are shown in Figure 3 for the cell driven by the normal method. The off time increases initially and decreases as the pretilt increases, and then decreases with increasing voltage. The off time cannot remain a constant. The fluid directions are the same on both sides of the bend cell, and the fluid velocity increases on approaching the centre of the cell, so the torque induced by this flow accelerates the relaxation of LC molecules, and becomes stronger as the pretilt angle and drive voltage increase (*10*). For this reason, the off time becomes very fast for high pretilt angles and high drive voltages.

The off times of the cell switched from V_{on} to U_c by using the under-shoot method are shown in Figure 4. Figure 4(a) shows the off times calculated using Equation (7), and Figure 4(b) those simulated using Equation (1). As can be seen in Figure 4, the fastest response appears at the low pretilt angle, which has been confirmed by the experimental data when the cell is driven by the under-shoot method (4), and the off time of the cell that has non-zero critical voltage is faster than that of the cell driven by the normal method. For a cell with low pretilt, θ_c is much larger than that of the cell with high pretilt, so the off time of the cell with low pretilt is faster than that of the cell with high pretilt from Equation (7). For the cell with high pretilt, θ_c is small and the off time is only dependent on $\overline{F(\theta)}$ in Equation (9); it decreases with increasing voltage because $\overline{F(\theta)}$ decreases as the voltage increases. With increasing voltage, the LC molecules turn so that they are perpendicular to the substrate, so θ_m increases and $\overline{F(\theta)}$ decreases; as a result, the off time tends to a constant using Equation (7), as can be seen in Figure 4. In a Freedericksz cell with the same parameters, the decay time is $\tau_0=\gamma d^2/\pi^2 K\sim 10$ ms. In Figures 3 and 4, the decay time is much faster than that of a Freedericksz cell, which can also seen from Equations (4) and (7).

Comparison of Figures 3 and 4 indicates that the results calculated by the analytical equation and dynamic equation agree with each other for high pretilt angles, but do not at low pretilt angles. For a cell with high pretilt, the critical voltage is small or equal to zero, so the LC deformation driven by the critical voltage is very little and our small-angle approximation is correct in analytical processes (11). For a cell with low pretilt, the LC deformation induced by the high critical voltage is large; as a result, the maximum changes of tilt angle do not

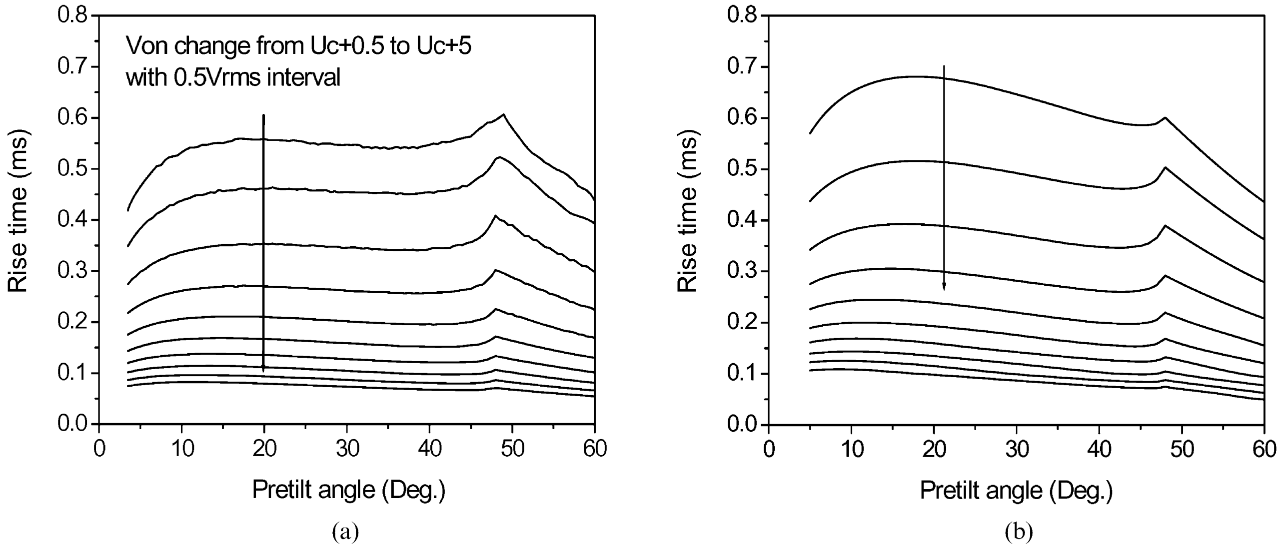

Figure 2. The rise times (a) calculated by Equation (5) and (b) simulated using Equation (1) of the cell switched from U_c to V_{on} for the cell with different pretilt angles.

appear at the quarter and three-quarter layers in the bend cell, so our small-angle approximation is inapplicable in this case, but as an approximation, the results using the small-angle approximation are close to the results of simulation.

3. Summary

In conclusion, the response times have been calculated in detail for a Pi-cell LCD. For the cell driven by the normal method, the response times (both rise and off times) increase as the voltage increases. For the cell driven by under-shoot method in the decay process, the off time is improved and increases as the voltage increases for the cell with non-zero critical voltage. These results have potential application in the future design of Pi-cell LCDs with faster response speeds.

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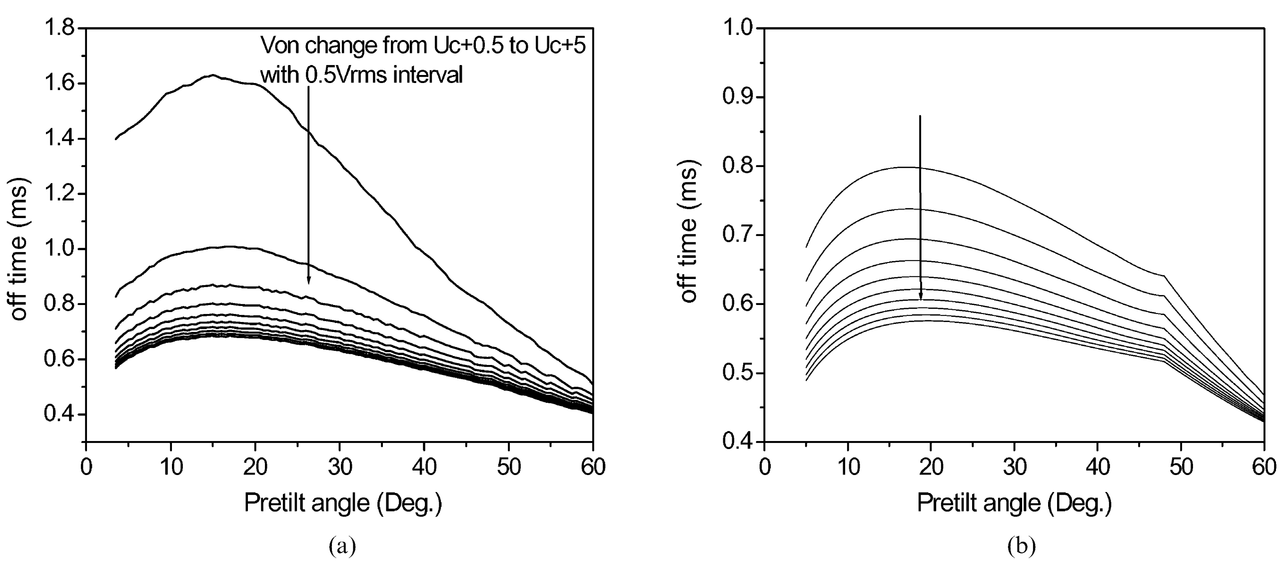

Figure 3. The off times (a) calculated by Equation (4) and (b) simulated using Equation (1) of the cell switched from U_c to V_{on} for the cell with different pretilt angles using the normal method.

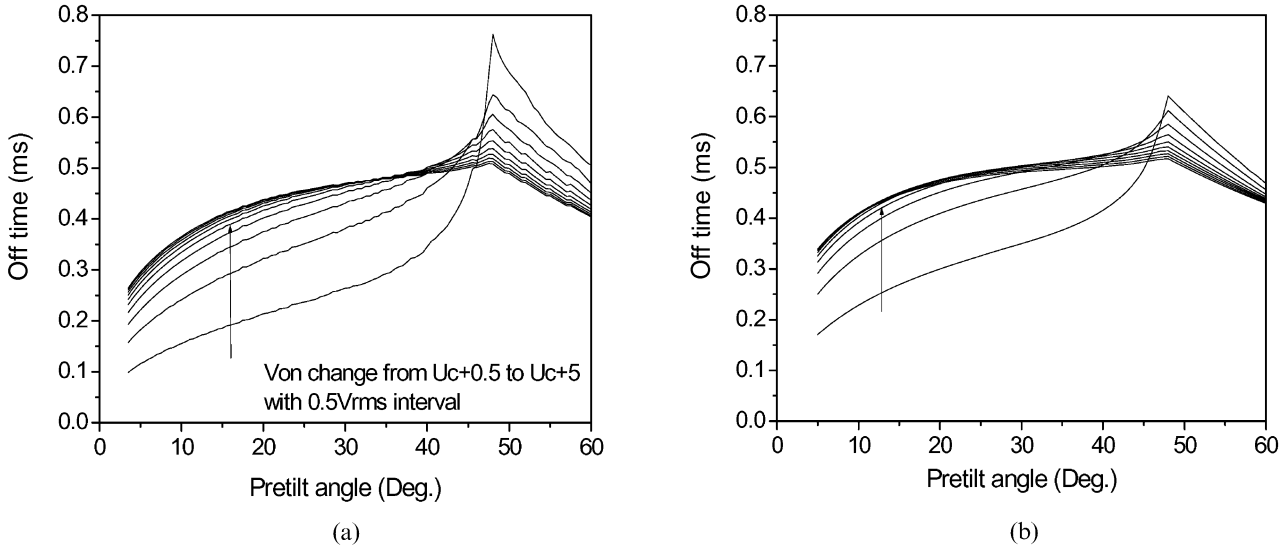

Figure 4. The off times (a) calculated by Equation (7) and (b) simulated using Equation (1) of the cell switched from U_c to V_{on} for the cell with different pretilt angles using the under-shoot method.

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